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ARMY CANNON FATIGUE LIFE EVALUATION: CRACK INITIATION, FRACTURE MECHANICS, AND NDI

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13. ABSTRACT *(Maximum 200 words)*

Laboratory hydrostatic test results and fracture mechanics analysis from cannon fatigue life investigations are used (1) to demonstrate the large changes in total fatigue life caused by the initial crack size and the levels of applied and residual stress at the cannon bore, and (2) to compare ultrasonic nondestructive inspection (NDI) measurements of crack growth and cannon fatigue life measurements with fracture mechanics-based crack growth and life analyses. The cannons of this investigation have 120-mm inner diameter, a nominal 75-mm wall thickness, and are made from ASTM A723 Ni-Cr-Mo-V steel, quenched and tempered to 1120 MPa yield strength.

Problem Solution: The methods of testing and analysis are believed to be generally applicable to problems in fatigue life evaluation of pressure vessels, particularly to gain an understanding of the effects of crack size, applied and residual stress, and vessel configuration on the service fatigue life. Procedures and results are presented which show the importance of initial crack size obtained from NDI methods in determining the fatigue lifetime of cannons and other pressure vessels.

Unresolved Problem: An unresolved problem will be presented for possible solution, that being the need for an NDI method to accurately measure initial crack sizes at a cannon bore. Characterization of the thermally-induced cracking at a cannon bore is a difficult problem, since a network of closely-spaced, very short (~0.1-mm) cracks is produced in a layer that is also severely thermally altered from that of the base material.

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OBJECTIVE

The evaluation of large caliber Army cannon tubes to ensure safe operation in service is performed using a prescribed combination of full-scale fatigue life tests and associated engineering analysis. Final prototype cannons are fired to produce realistic thermal damage and crack initiation at the bore surface, and subsequently laboratory pressure tested in sections under critical service conditions. These tests are used to determine a conservative safe life that virtually eliminates the chance of a fatigue failure during service. However, improved descriptions of cracks and predictions of fatigue life would lead to considerable savings in time and cost. To accomplish this, fracture mechanics calculations are used to show the effects of crack size on fatigue life and NDI methods are used to monitor crack growth in cannons during fatigue testing. These are the general objectives of this report.

The specific objective is an extension of recent work (ref 1) in which the effects on fatigue life of erosion at the cannon inner radius were investigated. Erosion grooves resulted in a significant reduction in life, but such erosion grooves are not always present, whereas thermal damage of the cannon inner radius is always present to some degree. In this report the effects of thermal damage on fatigue life will be addressed, with emphasis on the initiation and early growth of thermal-damage cracks at the cannon inner radius. First, *fatigue life calculations* will be described, using the approach of fracture mechanics to show the effect on life of various factors, including pressure, residual stress, and initial crack size. Second, results of *pulse-echo ultrasonic NDI* measurements will be used to describe some aspects of fatigue crack growth in cannons. Finally, an *unresolved NDI problem* related to cannon fatigue testing will be presented, that of characterizing the initiation and early growth of thermal-damage cracks at a cannon inner radius at the start of the fatigue failure process.

FATIGUE LIFE CALCULATIONS

Fracture Mechanics Analysis

A simple, short-crack analysis of stress intensity factor, K, and fatigue life was used to calculate lives, in an approach similar to that in recent work (ref 1). The simple approach was used so that the factors that have most effect on life could be readily seen and also because experience has shown that the dominant control of fatigue life is from short cracks. Starting with the experimentally-determined relationship (ref 2) describing the fatigue crack growth per cycle, da/dN, in terms of the stress intensity range, ΔK, we have

$$da/dN = 6.52 \times 10^{-12}\, \Delta K^3 \qquad (1)$$

where the constant 6.52×10^{-12} and the power 3 describe the growth rate for the A723 steel used and are appropriate for da/dN in m/cycle and ΔK in MPa $m^{1/2}$. ΔK is determined using the familiar expression for an edge crack, as follows (ref 3):

$$\Delta K = 1.12\, (\pi\, a)^{1/2}\, S_{eff} \qquad (2)$$

where S_{eff} is a combined effective stress that includes the stresses due to applied pressure, S_P, and the residual stresses, S_R, that may be present in the tube wall. The expression for S_{eff} is

$$S_{eff} = S_P + S_R \tag{3}$$

where S_P is the circumferential stress at the tube inner radius due to pressure at the crack (ref 4), plus an added stress equal to the pressure to account for the pressure acting on the crack faces,

$$S_P = p[W^2 + 1]/[\ W^2 - 1] + p \tag{4}$$

and S_R is the circumferential residual stress at the inner radius of a fully overstrained tube (ref 5),

$$S_R = S_Y[1 - \mathit{ln}\ W(2W^2/(W^2\text{-}1)] \tag{5}$$

In equations (4) and (5), p is pressure, W is the ratio of outer to inner radius of the tube, $r_2/\ r_1$, and S_Y is the yield strength of the tube material.

An expression for fatigue life, N, can be written by integrating Equation (1) and combining the result with Equations (2) through (5) to give

$$N = 2[1/\sqrt{}a_i - 1/\sqrt{}a_f]/6.52 \times 10^{-12}[1.12\sqrt{\pi}(S_P + S_R\ ]^3 \tag{6}$$

where the term $2[1/\sqrt{}a_i - 1/\sqrt{}a_f]$ is from integration and the other terms are from Equations (2) through (5). Equation (6) can be used to calculate fatigue life with account of the key factors that control fatigue life in a pressurized, overstrained thick-wall tube. These factors, referring also to terms and parameters in the above equations, are:

- Initial and final crack depths (a_i , a_f)
- Material crack growth properties (6.52×10^{-10} and power 3)
- The edge crack nature of the overall configuration ($1.12\ \sqrt{\pi}$)
- Pressure, p, on the inner radius and crack surfaces (S_P)
- The overstrain residual stress (S_R)
- Ratio of outer to inner radius of the tube (r_2/r_1)
- Material yield strength (S_Y)

Effects on Fatigue Life

Often, many of the fatigue life-controlling parameters in the above equations are fixed by the design of the cannon or other type of pressure vessel, such as the outer and inner radii, r_2 and r_1, and the material yield strength, S_Y. Other parameters can vary, depending on how the tube is manufactured and used in service. Three parameters that have significant control over fatigue life are illustrated in Figure 1.

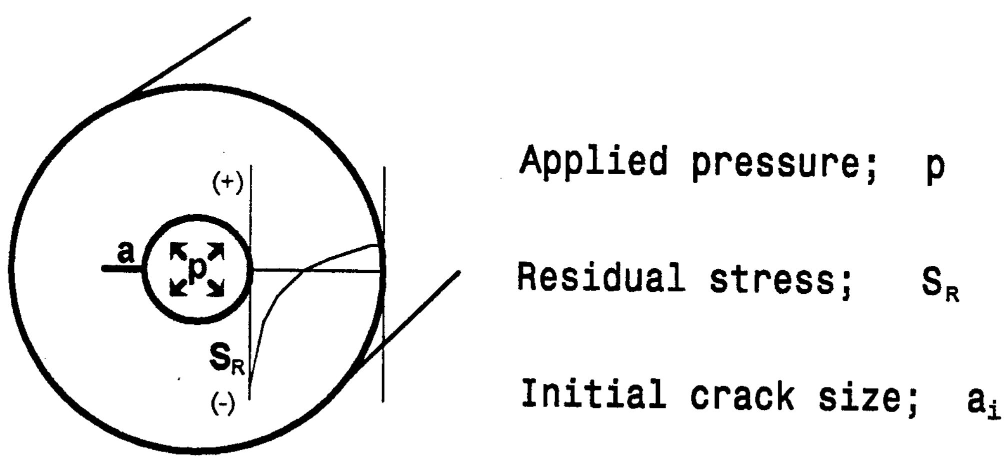

Figure 1 - Factors that control fatigue life of a cannon tube

The pressure applied to the inner radius of the tube is the basic loading parameter for a pressure vessel and thus has significant effect on fatigue life. As shown by Equation (4), the pressure applied to the crack surfaces is also important, because it adds to the total effective stress that causes crack growth, as shown in Equation (3). Any residual stress that is present in pressurized tubes can affect fatigue life. An overstrained residual stress is typically used with cannons and some other pressure vessels used for industrial processes. By plastically deforming the tube through the application of an overpressure or an oversized mandrel, a compressive residual stress is produced near the inner radius, as sketched in Figure 1. A balancing tensile residual stress is produced near the outer radius, but the tensile stress has no deleterious effect if there are no significant stress concentrators at the outer radius. The net effect of both types of residual stress is an increase in fatigue life of the tube. The compressive residual stress at the inner radius counteracts the tensile applied stress due to the pressure, and thereby slows the initiation and growth of fatigue cracks.

Typically, the factor that has the strongest control over fatigue life of a cannon tube or other pressure vessel, and the factor of importance to NDI, is the initial crack size present at the inner radius. Consideration of the $1/\sqrt{a_i}$ term in Equation (6) shows a so-called singular behavior, that is, as a_i approaches zero, the life, N, approaches infinity. So, in the case of a carefully made tube (at relatively low applied pressure) with only very small defects on the inner radius, a long life is expected, whereas a tube with the same configuration and pressure but with a_i of significant size, due to different manufacturing or service, would have a much shorter life, shorter by a factor of 10 or even 100 in some cases.

Calculations were performed to show the effects on fatigue life of applied pressure, p, residual stress, S_R, and initial crack size, a_i, for the configurations and loading of a 120-mm inner diameter cannon; see Figures 2 and 3. Comparisons were made with results from laboratory hydrostatic tests of a section from a 120-mm tank cannon. Calculated plots of crack size versus number of fatigue cycles, a versus N, were made using Equation (6) with the following input values, typical of the test section of the cannon tested: $a_i = 0.1$-mm, $a_f = 76$-mm, p = 670 MPa, $r_2 = 154$-mm, $r_1 = 78$-mm, $S_Y = 1120$ MPa. The input values were determined directly from the cannon tested, except for the value of a_i, 0.1-mm. This is believed to be a good estimate of the initial crack depth, based on results discussed in the upcoming section on fatigue crack measurements.

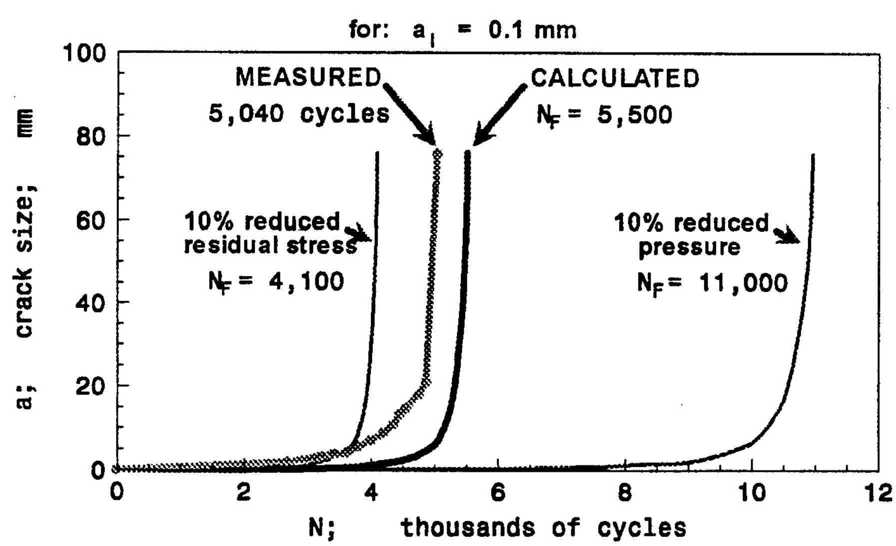

Figure 2 - Measured and calculated fatigue crack growth for cannon

Figure 2 compares the measured and calculated a versus N plots for the nominal values of p and S_R given above, and also for 10 percent reductions in each of these values. Note first that the calculated life for the nominal values of p and S_R is 9 percent higher than the measured life, which is considered to be good agreement, considering the many factors already discussed that can affect fatigue life. It is also worth noting the significant effect that a relatively small reduction in p or S_R has on the calculated life. A 10 percent reduction in S_R causes a 25 percent reduction in life, and a 10 percent reduction in p causes a 100 percent increase in life. For these calculations, p has more effect on life than S_R, but this is not always the case. For a situation with a lower value of p relative to the value of S_R, the two terms in Equation (3), S_P and S_R, are closer in magnitude and of opposite sign, so a change in either term has a significant effect on life.

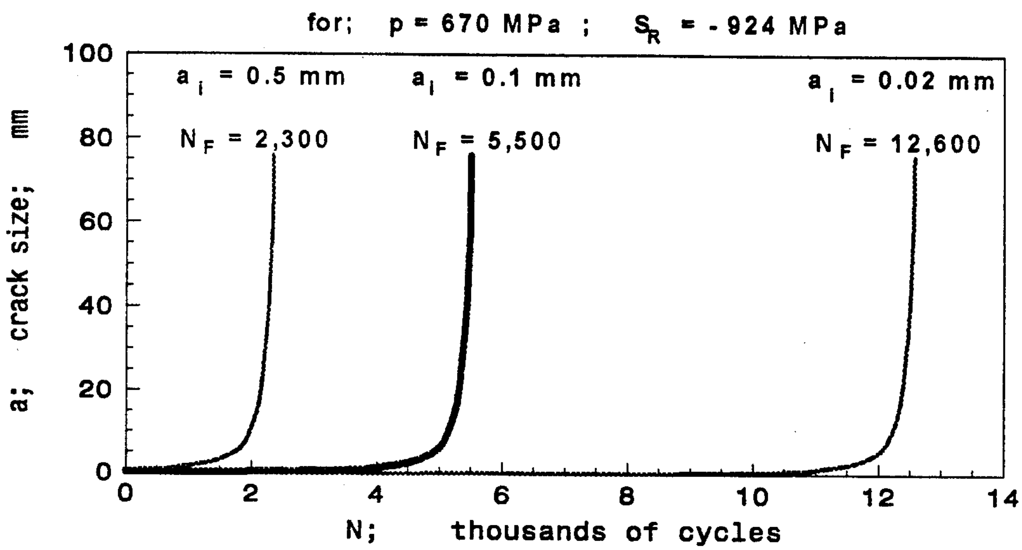

Figure 3 - Effect of initial crack size on fatigue life for cannon

Figure 3 shows the effect on fatigue life due to changes in the initial crack size, a_i, for the same nominal values of p and S_R described earlier. The $a_i = 0.1$ plot in Figure 3 is the same as the calculated plot in Figure 2. Note the significant changes in calculated fatigue life that are indicated for small changes in the absolute value of a_i, changes involving a fraction of a millimeter crack size. This emphasizes both the importance of a_i in controlling fatigue life and the difficulty in making useful descriptions of fatigue life - unless accurate and sensitive NDI information is available. These topics will be discussed further in the upcoming section on fatigue crack measurements.

FATIGUE CRACK MEASUREMENTS BY NDI

Monitoring Crack Growth

A pulse-echo ultrasonic crack measurement method has been used to locate the dominant fatigue crack that grows from a tube inner radius and to follow the growth of the crack until failure. Two examples of this monitoring of the dominant fatigue crack in cannon tubes are shown in Figure 4. Crack growth results from a tube that experienced a severe type of localized erosion in the form of 3-mm deep grooves are shown on the left of Figure 4. A crack was detected growing from one of the more severe erosion grooves after about 2000 pressure cycles, and grew through the wall thickness, 71-mm at this tube location, after 3390 cycles. Results from another tube with no localized erosion are also shown. A crack grew from the thermally damaged area at the cannon bore and through the wall, 76-mm at this location, after 5040 cycles.

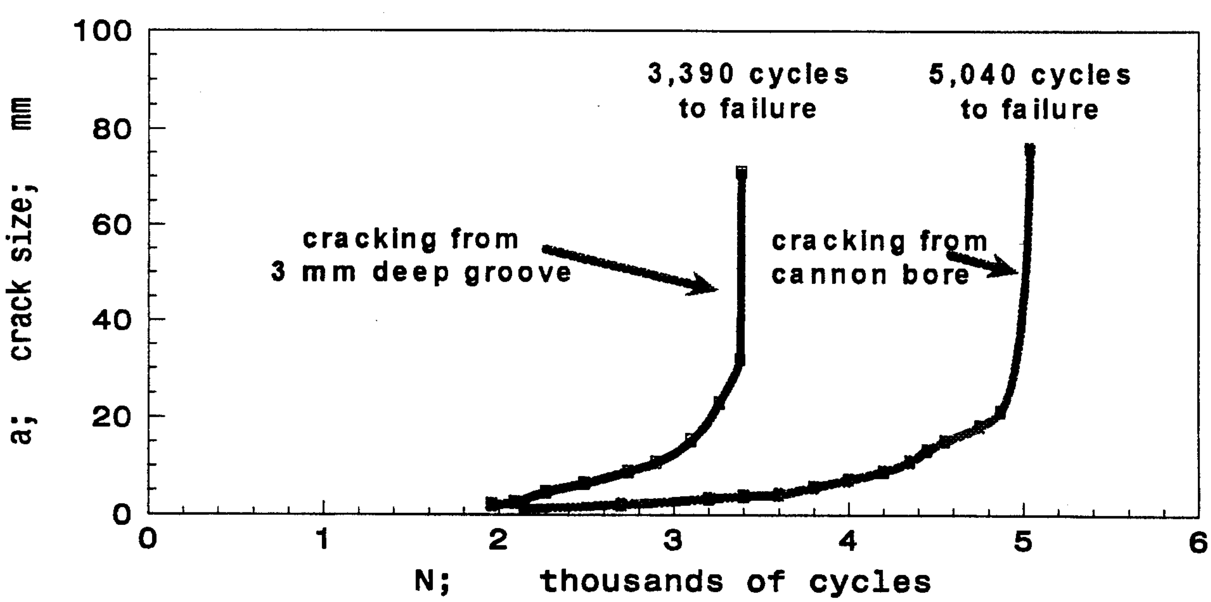

Figure 4 - Measured fatigue crack growth using pulse-echo ultrasonics

These examples of ultrasonic crack measurement show advantages of the method as well as a limitation, discussed as follows. The method can be used for cracking of different type and starting configuration, as seen in the monitoring of cracks from grooves or from the relatively smooth cannon bore. The crack measurements also give some understanding of the cause of cracking. Note, for example, that the rate of crack growth from the erosion groove is significantly faster than that from the smooth bore, which is an indication of the concentrated stress ahead of the erosion groove.

The basic limitation of the ultrasonic method for cannon applications is its lack of sensitivity in detecting and monitoring short cracks, and as discussed earlier, it is short cracks that have primary control of fatigue life. The features such as localized erosion grooves and thermally-altered layers at the cannon bore, that are the source of cracking, also interfere with the measurement of short cracks. Note in Figure 4 that cracks are first detected at about half the number of cycles of final failure, and detection of cracks at this point was based on careful mapping of numerous NDI indications and considerable experience with cannons. Characterization of cracks early in the life of cannon tubes is an important problem that needs resolution, and will be discussed next.

An Unresolved Problem

A schematic summary of the problem of NDI of short cracks in cannons is shown in Figure 5. At the top of the figure is half of a tube cross-section showing the two types of cracking under consideration in this report. Cracking at an erosion groove is a problem in the sense that the fatigue life is significantly reduced, as has been discussed. But it is not an NDI problem, because cracking at any groove or other stress concentrator is usually anticipated and well characterized by tests or analysis. It is the cracking at a thermally-altered bore surface of a cannon that presents a difficult problem. When severe erosion does not occur, cracking from an area of thermal damage is often the source and cause of failure of a cannon tube. To prevent or retard the thermal damage, a 0.1-mm layer of chromium is typically electroplated on the bore, as was the case with the 120-mm cannon tubes under discussion.

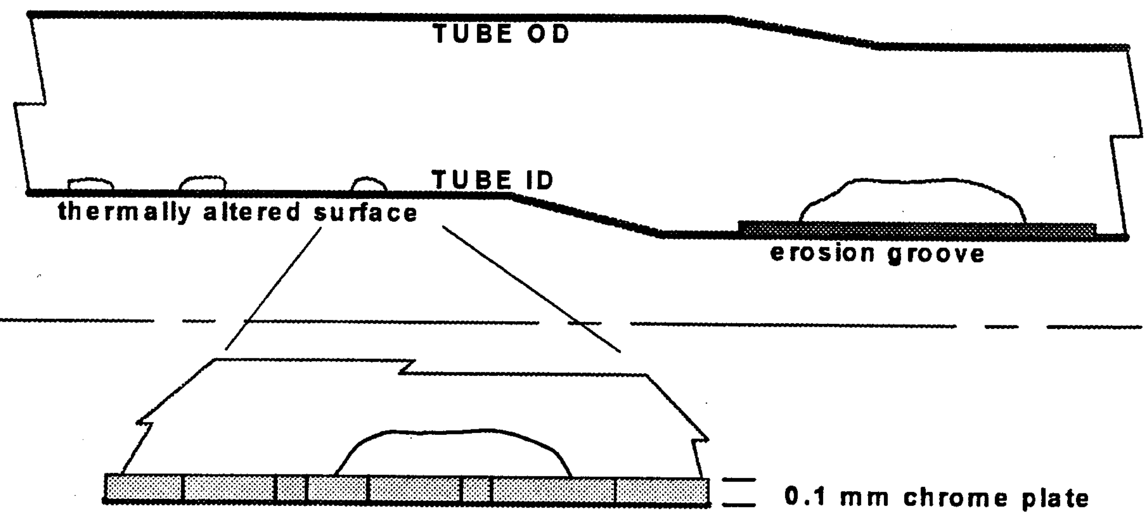

Figure 5 - Unresolved NDT problem; characterization of fatigue crack initiation in a cannon tube

The typical appearance of the crack initiation site on the fracture surface (as viewed by a scanning electron microscope) is shown in the lower sketch of Figure 5. It appears that thermal stresses from cannon firing enlarge the cracks that are typically present in the plated chromium, and then thermal and mechanical stresses initiate a crack in the steel under the chromium plate, as shown. Characterization of this critical initiation and early growth of cracks in the thermally-affected bore surface is an important unresolved problem. If NDI methods could (1) determine the number of firing cycles required for the chromium cracking and for the initiation of steel cracking, and (2) help determine the factors that control the cracking in both materials, an important problem would be well on the way to resolution. With this information, more accurate and efficient safe fatigue life assessments could be made for cannons, with considerable time and cost savings.

SUMMARY

1. Fracture mechanics calculations of fatigue crack growth and fatigue life were shown to agree well with hydrostatic pressure fatigue tests of sections of 120-mm full-scale cannon tubes. The calculations account for applied and residual stresses, as well as for the critical initial crack size at the inner radius of the tube.

2. Significant effects of initial crack size on fatigue life of a cannon tube were presented, demonstrating the important interconnection between fracture mechanics analysis and nondestructive evaluation. For the load and configuration conditions typical of a 120-mm cannon, changes in the initial crack size by fractions of a millimeter result in a factor-of-five change in the calculated fatigue life.

3. Pulse-echo ultrasonic NDI crack measurements successfully monitored the growth of cracks after they had grown to more than 2-mm in size near areas of thermal damage on the cannon inner surface. Distinctions in the rate of crack growth per loading cycle were easily documented for different levels of concentrated stress near the inner surface.

4. An unresolved problem was presented regarding the characterization of initiation and early growth of cracks within 1-mm of the thermally-affected cannon bore surface. NDI methods are needed to determine the number of loading cycles required for early cracking and the factors that control it, so that better fatigue life assessments could be made for cannons.

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